THREE PROBLEMS IN FLUID DYNAMICS

~ *FINAL REPORT* ~

Daniel D. Joseph, P.I.

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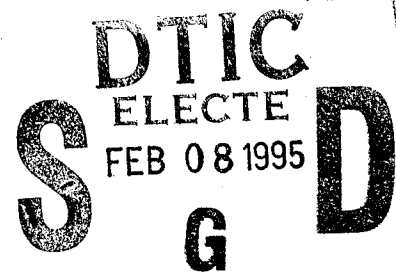
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Three problems were proposed for study. The first was to determine the fluid dynamics of spin-up of two fluids in a rotating container. The applications of these studies are the the problem of stabilization of rotating liquid-filled artillery shells in free flight and to the determination of the rheological properties of blends of polymers used to fabricate plastic composites with improved material properties. The second problem is to study the motion of solid particles in a flowing viscous fluid by direct numerical simulation of the Navier-Stokes equations and the particles equations of motion. The third problem was to identify correct physical mechanisms to regularize ill-posed problems which arise in the study of two-phase flows of bubbly mixture in spinoidal regions of phase change mixtures of vapour bubbles in liquids.

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1. Forward

This is the final report for the grant to Daniel D. Joseph, University of Minnesota, on "Three Problems in Fluid Dynamics," ARO Contract No. DA/DAAL03-91-G-0181. This final report gives a summary of all the works which were produced under this grant.

2. Research Accomplishments

2.A. Motivation, Technical Objectives and Approach; and Signification Scientific Accomplishments

This project was funded in April 1991 for work on three problems. The first problem was to determine the spin-up dynamics of two fluids in a rotating container. A numerical and accurate approximate analytical solution of the problem was obtained in the paper entitled "Evolution of Liquid Drop in a Spinning Drop Tensiometer" by Hu and Joseph (see §2.C of this report). The formulas in that paper describe the motions which develop under a step change of angular velocity, and they identify the material parameters that enter into the relaxation to be used with the interfacial tensiometer (U.S. Patent 5,150,607). The extended theory will make it possible to measure relaxation parameters as well as interfacial tension at different temperatures with the same device. The spinning drop device together with the extended theory is at present without a competitor and it has a niche in applications which relay heavily on effects of surfactants, particularly in industries which process emulsions and foams.

The second problem was to study the motion of solid particles in a direct numerical simulation using the Navier-Stokes equation for fluids and Newton's equations for rigid solids. The simulations are used to determine microstructural properties of fluidized suspensions of a few particles at moderate values of the Reynolds number in the 100's. From these simulations, one can identify the mechanisms which give rise to lateral migration of particles and turn the broadside of long bodies perpendicular to the stream. It is found that a viscous "stagnation" point is a point on the body where the shear stress vanishes and the pressure is nearly a maximum. The migration is controlled by stagnation and separation points. The lift-off and steady flight of solid capsules in Poiseuille flows is analyzed in a two-dimensional simulation. A three-dimensional simulation of steady flow at slow speeds shows that the extensional stresses in a viscoelastic flow change the sign of the normal stress which would exist at points of stagnation in a Newtonian fluid, causing the longside of the body to line up with the stream. This program has been very productive; thirteen papers were written. A summary of this work is given in the review paper, "Interrogation of Numerical Simulations for Modeling of Flow-Induced Microstructure," which is listed in the references of §2.C of this report.

The third problem was to identify the physically-correct mechanisms to regularize ill-posed problems which arise in the study of two-phase flows of bubbly mixtures. A book on "Short Wave Instabilities and Ill-Posed Problems" by Daniel D. Joseph and Jean Claude Saut is being prepared. New results on this topic were not obtained in 1993.

A number of informal reports on the topic of drop breakup of viscoelastic liquids at high Mach number were written and circulated to responsible scientists at ERDEC (Pat Nolan, Miles Miller) and SSDC (Tim Cowles, Bob Becker). This work is going to be expanded. Plans are underway to build a Mach 8 shock tube to examine the breakup under realistic conditions.

2.B. Awards and Honors

Professor Joseph was elected to the American Academy of Arts and Sciences in 1993. He is the only faculty member at the University of Minnesota ever to be elected a member of all three academies (NAE, NAS, AAAS). He was also awarded the Bingham Medal of the Society of Rheology (his work in rheology has been supported by the ARO for nearly 20 years). He was elected to the rank of fellow the American Physical Society (in fluid mechanics), and he received an unrestricted research grant for excellent works on the theory of viscoelastic flows from the Schlumberger Foundation. Most recently, Professor Joseph was awarded the University of Minnesota Board of Regents' Professorship.

2.C. List of Recent Publications (Since 1991)

"Two-dimensional cusped interfaces" (with John Nelson, M. Renardy, and Y. Renardy) *Journal of Fluid Mechanics* **223**, 383–409 (1991).

"Lubricated pipelining: Stability of core-annular flow. Part V: Comparison of linear stability and experiments" (with R. Bai and K. Chen), *Journal of Fluid Mechanics* **240**, 97-122 (1992).

"Lubricated pipelining: Stability of core-annular flow. Part IV: Ginzburg-Landau equations" (with K. Chen), *Journal of Fluid Mechanics* **227**, 587-615 (1991).

"Determination of the equilibrium trajectory of a cylinder in two-dimensional flow by direct simulation" (with T. Hesla), to be submitted to *Journal of Fluid Mechanics*.

"Dynamics of fluidized suspensions of spheres of finite size" to appear in *International Journal of Multiphase Flow* (1993).

"Mathematical problems for miscible, incompressible fluids with Korteweg stresses" (with P. Galdi, L. Preziosi and S. Rionero), *European Journal of Mechanics B/Fluids* **10**(3), 253-267 (1991).

"Vortex rings of one fluid in another in free fall" (with N. Baumann, P. Mohr, and Y. Renardy). *Physics of Fluids* A, **4**(3), 567-580 (1992).

Fluid Dynamics of Viscoelastic Liquids. Springer Applied Math Series (number 84), 1990.

"Combined effects of riblets and polymers on drag reduction in pipes" (with C. Christodoulou and K.N. Liu), *Physics of Fluids*, A **3**(5), 995-996 (1991).

"Miscible displacement in Hele-Shaw cells" (with H. Hu), UMSI preprint (1990). ZAMP, **43**, 626-644 (1992).

"Remarks on long wave and lubrication theories for core-annular flow" (with K. Chen), Physics *of Fluids* **3** (11), 2672 (1992).

"Elastic short wave instability in extrusion flows of viscoelastic liquids" (with K. Chen), *Journal of Non-Newtonian Fluid Mechanics* **42**, 189-211 (1992).

"Kelvin-Helmholtz mechanism for side branching in the displacement of light with heavy fluid under gravity" (with T.Y.J. Liao and J.-C. Saut), *European Journal of Mechanics B/Fluids* **11** (3), 253-264 (1992).

"Separation in flowing liquids," *Nature* **348**(December), 487 (1990).

"Non-solenoidal velocity effects and Korteweg Stresses in simple mixtures of incompressible liquids" (with H. Hu), AHPCRC preprint 91-03 (1991). Chapter 10: Fundamentals of Two-Fluid Dynamics, Springer, (1992).

"Interfacial tension between miscible liquids" (with H. Hu), AHPCRC preprint 91-58. Chapter 10: Fundamentals of Two-Fluid Dynamics, Springer, (1992).

"Direct simulation of fluid-particle motions" (with H. Hu and M.Crochet), AHPCRC preprint 91-43, *Journal of Theoretical and Computational Fluid Dynamics* **3**, 285-306 (1992).

"Wake Architectures in Two-Dimensional Fluidization of sphere to Experiments and Phenomenological description" (with A. Fortes). Proceedings of joint DOE/NSF workshop on flow of particulates and fluids, Worcester MA, October 22-24 (1991).

"Finite size effects in fluidized beds in liquid-solid flows" FED 118, (eds. M.C. Roco and T. Magasume), *American Society of Mechanical Engineers*, 77-86 (1991).

"Nonlinear and finite size effects in fluidized suspensions" Particulate Two-phase flow, Chapter 10 (ed. M. Roco) Butterworth Heinemann, (1992).

"Upper and lower bounds for interfacial tension using spinning drop devices"(with M. Arney and G. Ma), *Journal Colloid & Interfacial Science* , **148**(1), 291-294 (1992).

"Instability of the equilibrium of a liquid below its vapor between horizontal heated plates" (with A. Huang), *Journal Fluid Mech*. **242**, 235-247 (1992).

"Stability of liquid-vapor flow down an inclined channel with phase change" (with A. Huang), *Int. J. of Heat and Mass Transfer,* **34**(3), 663-673 (1993).

"Applications of binary sequences to problems of chaos" *Video Journal of Engineering Research*, **1** (2), 107-114 (1992).

"A spinning drop tensioextensiometer" (with M. Arney, G. Gillberg, H. Hu, D. Hultman, C. Verdier, H. Vinagre). *J. Rheology* , **36**(4), 621-662 (1992).

"Understanding cusped interfaces" *J. Non-Newtonian Fluid Mech.* **44**, 127-148 (1992).

"The Tilt Transition and Potential Flow." Plenary lecture at the 1st International Symposium of the Grenoble Mechanics Federation, May 19-21 (1992). To appear in the Proceedings.

"Competition between inertial pressures and normal stresses in the flow induced anisotropy of solid particles" (with J. Nelson, H. Hu and Y. J. Liu). "Theoretical and Applied Rheology" (ed. P. Moldenaers and R. Kuenings, pgs. 60-64, Elsevier, (1992).

"Experiments and direct simulations of fluid particle motion" (with H. Hu and A. Fortes). *Video J. Eng. Res.* **2**, 17-24 (1992).

"Bernoulli equation and the competition of elastic and inertial pressure in the potential flow of a second order fluid." *J. Non-Newtonian Fluid Mech.* **42**, 385-389 (1992).

"Drag and moment in viscous potential flow" (with T.Y. Liao and H.H. Hu), *European J. Mech B/Fluids* **12**(1), 97-106 (1993).

"Friction factor and holdup studies for lubricated pipelining" (with M.S. Arney, R. Bai, E. Guevara, and K. Liu). *Int. J. Multiphase Flow* **19**(6), 1061-1076 (1993).

"A discussion on the aerodynamic dissemination of simulant released at high altitude" (with A. Huang and M. Arney). Proceedings of the 1992 US Army Chemical Research Development and Engineering Center. Scientific conference on Chemical Defense Research. Nov. 18, 1992.

"Orientation of long bodies falling in a viscoelastic liquid" (with Y.J. Liu). *J. Rheol.* **37**(6), 961-984 (Nov/Dec 1993).

"Anomalous rolling of spheres down an inclined plane" (with Y.J. Liu, J. Nelson and J. Feng). *J. Non-Newtonian Fluid Mech.* **50**, 305-329 (1993).

"Potential flows of viscous and viscoelastic fluids" (with T. Liao), *J. Fluid Mech* **265**, 1-23 (March 1994).

"A note on the net force and moment on a drop due to surface forces" (with T. Hesla and A.Y. Huang) *J. Colloid & Interface Science* **158**, 255-257 (1993).

"Independent confirmation that delayed die swell is a hyperbolic transition" (with C. Christodoulou). *J. Non-Newtonian Fluid Mech.* **48**, 225-235 (1993).

"Sedimentation of particles in polymer solutions" (with Y.J. Liu) *J. Fluid Mech.* **225**, 565-595 (1993) and AHPCRC preprint 92-076.

"Direct simulation of initial value problems for the motion of solid bodies in a Newtonian fluid" (with J. Feng and H. Hu). *J. Fluid Mechanics* **261**, 95-134 (1993).

"A three-dimensional computation of the force and moment on an ellipsoid settling slowly through a viscoelastic fluid" (with J. Feng, R. Glowsinski and T.W. Pan). MSI Preprint 93/217 (1993).

"Viscous and viscoelastic potential flow" (with T. Liao). To appear in "Trends and Perspectives in Applied Mathematics" *Applied Mathematical Sciences* **100**, Springer-Verlag, New York (1994) and AHPCRC preprint 93-010.

"Aggregation and dispersion of spheres falling in viscoelastic liquids" (with Y.J. Liu, M. Poletto and J. Feng). *J. Non-Newtonian Fluid Mech* **54**, 45-8. (1994).

"White-Metzner models for rod clmbing in A1" (with T.Y. Liao and H.H. Hu). Accepted for publication in *J. Non-Newtonian Fluid Mech* (1994).

"Friction factor and holdup studies for lubricated pipelining. Part II: laminar and k-ε models of eccentric core flow" (with A. Huang and C. Christodoulou). Accepted for publication in *Intl. J. of Multiphase Flow* (1994).

"The turning couples on a elliptic particle settling in a vertical channel" (with P.Y. Huang and J. Feng). *J. Fluid Mech.* **271**, 1-16 (1994).

"Direct simulation of initial value problems for the motion of solid bodies in a newtonian fluid. part 2: couette and poiseuille flows" (with J. Feng and H. Hu). Accepted for publication in *J. Fluid Mech.* (1994).

"Stability of eccentric core-annular flow" (with A. Huang). Accepted for publication in *J. Fluid Mech.* (1994).

"Effects of frictional heating on the torque between rotating cylinders" (with C. Christodoulou and T. Blomstrom). AHPCRC Preprint. Submitted to *Phys. Rev. A* (1994).

"Parallel pipelining" (with H. Hu, R. Bai, T.Y. Liao and A. Huang). Accepted for publication in *J. Fluids Eng.* (1994).

"Dynamic simulation of the motion of capsules in pipelines." Accepted for publication in *J. Fluid Mech.*

"Non-solenoidal velocity effects and Korteweg Stresses in simple mixtures of incompressible liquids." To appear in *Proceedings of the Symposium on 'Applied Mathematics at the Turn of the Century,'* Universidad Complutense, Cursos de Verano, Almeria, Spain, July 5-10, 1993.

"Non-solenoidal velocity effects on the stability of diffusion in incompressible miscible liquids" (with A. Huang and H. Hu). Submitted to *European J. of Mechanics A, Fluids*.

"The effective density and viscosity of a suspension" (with M. Poletto). Accepted for publication in *J. Rheology* (1994).

"The negative wake in a second order fluid" (with J. Feng). Submitted to *J. Non-Newtonian Fluids*.

"A Maxwell memory model for the delayed weather reponse to solar heating" (with K.R. Sreenivasan). Submitted to *Proc. Roy. Soc. A*.

"Cavitation in a flow liquid." Submitted to *Physical Review E*.

"Adhesion of crude oil to wet ceramics" (with G. Ribeiro, M. Arney, M. Rivera and T. Hall). Submitted to *J. Colloid & Interfacial Sci.*.

"Interrogation of numerical simulations for modeling of flow induced microstructures." *ASME FED* **189** (Liquid-Solid Flows), 31-40 (1994).

"A three-dimensional computation of the force and moment on an ellipsoid settling slowly through a viscoelastic fluid." Accepted for publication in *J. Fluid Mech* (1994).

"The unsteady motion of solid particles in creeping flows" (with J. Feng). Submitted to *J. Fluid Mech*.

"Two-dimensional cusp at the brailing edge of an air bubble rising in a viscoelastic liquid" (with Y.J. Liu and T.Y. Liao). Submitted to *J. Fluid Mech*.

"Boundary layer flow of air over water on flat plate" (with J. Nelson and A. Alving). Accepted for publication in *J. Fluid Mech.* (1994).

"Cement-lined pipe for water lubricated transport of hydrocarbons" (with M. Arney, G. Ribeiro, E. Guevarra and R. Bai). Submitted to *Int. J. Multiphase Flow*.

2.D. *List of All Participating Scientific Personnel Supported by ARO Grant*

<u>Graduate Students</u>:

Michael Arney (Ph.D., 1994), Yadong Huang, YiJian Huang, Yi-Jen Liao,* Geraldo Ribeiro,* Yibing Wang.

*Ph.D. to be completed by end of current grant.